

*SIGNALLED AND UNSIGNALLED TERMINAL LINKS IN CONCURRENT CHAINS I: EFFECTS OF REINFORCER PROBABILITY AND IMMEDIACY*

KARLA M. MATTSON, ANDREW HUCKS, RANDOLPH C. GRACE, AND ANTHONY P. MCLEAN

UNIVERSITY OF CANTERBURY

Eight pigeons responded in a three-component concurrent-chains procedure, with either independent or dependent initial links. Relative probability and immediacy of reinforcement in the terminal links were both varied, and outcomes on individual trials (reinforcement or nonreinforcement) were either signaled or unsignaled. Terminal-link fixed-time schedules were varied across components within conditions to yield immediacy ratios of 1:2, 1:1 and 2:1. The probabilities of reinforcement were varied across conditions to yield reinforcer ratios of 1:5, 1:2, 2:1 and 5:1. Results showed that a model based on the generalized matching law provided a good description of response allocation, accounting for 92% of the variance overall. As expected, sensitivity to probability was greater in the unsignaled conditions. However, sensitivity to immediacy was also greater in the unsignaled conditions, suggesting that the effect of signaling terminal-link outcomes may not be limited to probability but apply to reinforcer variables in general. The effects of signaling can be explained in terms of conditioned reinforcement added to each alternative's outcomes in the matching law. There was some evidence for an interaction between reinforcer probability and immediacy, particularly for the dependent-schedules group, such that sensitivity to immediacy was greater at moderate rather than extreme reinforcer ratios. However, further analysis suggested that this could have been due to a ceiling effect on response allocation imposed by dependent scheduling. Overall, the present results show that the generalized matching law can provide a useful account of choice between outcomes that vary in both probability and immediacy of reinforcement.

*Key words:* concurrent chains, reinforcer probability, reinforcer immediacy, signaled reinforcement, key peck, pigeons

Choice has been a major topic of research since Herrnstein's (1961) report of matching of response allocation to relative reinforcer rate in concurrent variable-interval (VI) VI schedules. Early studies extended the matching relation in concurrent schedules to other dimensions of reinforcement. For example, Catania (1963) reported that relative response rate approximately matched relative reinforcer magnitude, and Chung and Herrnstein (1967) reported matching to relative reinforcer immediacy (i.e., the reciprocal of delay). An extended matching law framework, first proposed by Baum and Rachlin (1969; see also Baum, 1974), combines reinforcer variables

multiplicatively to define relative reinforcer "value":

$$\frac{B_1}{B_2} = c \left( \frac{R_1}{R_2} \right)^{a_R} \cdot \left( \frac{1/D_1}{1/D_2} \right)^{a_D} \cdot \left( \frac{M_1}{M_2} \right)^{a_M} = \frac{V_1}{V_2} \quad (1)$$

According to Equation 1, the concatenated matching law, response allocation matches the relative value of the choice alternatives, with value determined by several different reinforcer dimensions. In Equation 1,  $B$  is response rate,  $R$  is reinforcer rate,  $D$  is reinforcer delay,  $M$  is reinforcer magnitude, and  $V$  is reinforcer value, subscripted for Choice Alternatives 1 and 2. There are four parameters:  $c$ , which represents bias, and a sensitivity exponent for each reinforcer dimension ( $a_R$ ,  $a_D$ , and  $a_M$ ).

Herrnstein (1964) investigated the adequacy of the matching relation for responding maintained by conditioned rather than primary reinforcement, using the concurrent-chains procedure introduced by Autor (1960/1969). The concurrent-chains procedure is a similar experimental arrangement to concurrent schedules in that two or more schedules of reinforcement are presented simultaneously to the subject on different response keys.

This experiment formed part of the doctoral dissertation submitted to the University of Canterbury by Karla Mattson in 2005, and was presented to the New Zealand Behaviour Analysis Symposium, Christchurch, 2004.

Address correspondence and reprint requests to Randolph C. Grace or Anthony P. McLean, Department of Psychology, University of Canterbury, Private Bag 4800, Christchurch, New Zealand (e-mail: randolph.grace@canterbury.ac.nz) (e-mail: anthony.mclean@canterbury.ac.nz).

doi: 10.1901/jeab.2010.94.327

Responses during the choice phase or initial link are reinforced by a change in color of the key light and by allowing access to one of two mutually exclusive terminal links. Once a terminal link has been entered, the other key becomes dark and inoperative. Responses during a terminal link produce access to food according to a separate reinforcement schedule. Thus, the concurrent-chains procedure allows various dimensions of reinforcement (such as immediacy, magnitude or probability) to be manipulated in the terminal links, and the effects of these dimensions on choice to be studied using responding in the initial links.

Although Herrnstein's initial application of the matching law to concurrent chains was encouraging, it was discovered that relative response rate deviated from relative delay of reinforcement when the overall durations of either the terminal links or the initial links were varied (Davison 1983; Fantino, 1969). This result violates the assumption, implicit in Equation 1, that preference depends on relative, not absolute, values of reinforcement variables. Subsequently, Grace (1994) proposed an alternative model, still based on the matching law, which attempted to resolve this failure of the "relativity" assumption. The novel feature of Grace's model is that variables relating to the conditions in the terminal link (reinforcer immediacy and magnitude ratios in Equation 1) are raised to the power  $T_t / T_i$ , which is the ratio of the average terminal- and initial-link durations. This exponent captures the dependence of sensitivity to immediacy and magnitude ( $a_D$  and  $a_M$ ) on temporal context (i.e., the durations of initial and terminal links). In conditions where  $T_t = T_i$ , as in the experiments described below, Grace's model and Equation 1 are equivalent.

One of the most important assumptions of Equation 1 is that the effects on preference of different variables such as reinforcer rate, immediacy and magnitude, are independent and combine multiplicatively (additively in logarithmic form). This assumption has been tested in a variety of studies that have manipulated various combinations of these variables parametrically (e.g., Grace, 1995; Grace, Bedell, & Nevin, 2002; McLean & Blampied, 2001), and the general conclusion is that independence has been supported when relative, but not absolute, levels of reinforcer variables have been manipulated

(Berg & Grace, 2004; but cf. Elliffe, Davison, & Landon, 2008). However, one variable that has not received much attention in these parametric studies is reinforcer probability. Although it is well established that pigeons' choice in concurrent chains favors the alternative that delivers food with higher probability (e.g., Spetch & Dunn, 1987), research has not yet varied reinforcer probability parametrically in combination with other reinforcer variables. Such a study would provide a test of whether the effects of reinforcer probability are independent of, and combine additively with, other reinforcer variables.

An important factor in probabilistic reinforcement procedures is the degree to which terminal-link stimuli are correlated with the outcomes scheduled on individual trials. Distinctive stimuli may be associated with the scheduled outcome (reinforcement or nonreinforcement) on individual trials (*signaled*), or the same stimulus may be presented whether or not reinforcement is forthcoming (*unsignaled*). With unsignaled terminal links, the typical result is that response allocation in the initial links strongly favors the alternative on which terminal-link reinforcement is more likely (e.g., Kendall, 1974, 1985; Spetch & Dunn, 1987). With signaled terminal links, preference for the more reliable alternative is much reduced (e.g., Dunn & Spetch, 1990; Kendall, 1974, 1985). This attenuation in preference with signaling implies a reduction in sensitivity to reinforcer probability, known as the *signaling effect*. Because no prior studies have examined the effects of probability in combination with other reinforcer variables, it is unknown whether the signaling of outcomes affects only sensitivity to probability; it might also affect sensitivity to other reinforcer variables.

The aim of the present research was to investigate whether effects of reinforcer probability and immediacy on choice are additive and independent, for both signaled and unsignaled probabilistic reinforcement procedures. By varying immediacy and probability across series of signaled and unsignaled conditions, we planned to test whether signaling terminal-link reinforcer outcomes affected sensitivity to immediacy as well as probability. We used a multiple concurrent-chains procedure similar to that employed by Grace (1995) and Grace *et al.* (2002). Three different

concurrent-chains schedules were presented, in separate components, during each session. Components were distinguished by the color (red, white or green) of both response keys during the initial links and of the operative key in the terminal link. Relative immediacy of reinforcement was varied across components; 1:2 in the red component, 1:1 in the white component and 2:1 in the green component. Relative reinforcer probability in the terminal links was constant across components, and was varied across conditions (5:1, 1:5, 2:1, and 1:2). The VI schedules used in the initial links were constant across components and conditions. These conditions were conducted twice; once with the terminal-link outcomes (i.e., reinforcement or nonreinforcement) signaled, and once with them unsignaled. Thus, the experimental design allowed us to examine the effects of parametric variation in relative reinforcer probability at different levels of relative immediacy, for both signaled and unsignaled terminal links. Our primary goals were to characterize the effects of reinforcer probability and immediacy on choice and to test if they were additive and independent, as required by the matching law, and whether signaling terminal-link outcomes would reduce sensitivity to probability.

## METHOD

### *Subjects*

Eight mixed-breed pigeons, numbered 161 through 164 and 185 through 188, served as subjects. They were maintained at 85% of free-feeding body weights ( $\pm 15$ g) by postsession feeding of mixed grain when necessary. They were housed individually in a vivarium with a 12:12 hr light/dark cycle (lights on at 0700h), and with free access to grit and water. All had previous experience with a variety of experimental procedures.

### *Apparatus*

Eight standard three-key operant chambers were used, measuring 350 mm deep by 360 mm wide by 350 mm high. The 20-mm diameter response keys were located 260 mm above the floor and arranged in a row, 100 mm apart. A houselight was located 70 mm above the center key and a grain magazine with an aperture of 60 mm by 50 mm was located

130 mm below the center key. The grain magazine was illuminated when reinforcement (wheat) was made available. A force of approximately 0.1 N was required to operate each response key, and effective responses produced an audible feedback click. Each chamber was enclosed in a sound-attenuating box, and ventilation and masking noise were provided by an attached fan. The experiment was controlled and data collected using a MEDSTATE<sup>®</sup> notation program and a MED-PC<sup>®</sup> system interfaced to a microcomputer located in an adjacent room.

### *Procedure*

Because all subjects had previous experience in a variety of procedures, training began immediately in the first condition. Sessions were conducted daily at the same time (1100h and 1200h) with few exceptions. A three-component multiple concurrent-chains procedure was employed. Components were differentiated by the color of keylights (red, white or green) used for all stimuli in a trial. Components consisted of 24 concurrent-chains trials, presented in a block. Components were separated by a 3-min blackout and the order of presentation was randomized before each session. The houselight provided general illumination except when reinforcement was being delivered, during intercomponent blackouts, and during no-food terminal links in the signaled conditions (see below).

*Concurrent chains.* To extend the generality of our results we divided subjects into two groups of 4, one trained with independent scheduling in the initial links and the other with dependent scheduling. For both groups, trials began with the side keys illuminated with the color associated with the current component, signifying the initial link or choice phase of the procedure. For the group receiving dependent scheduling, terminal-link entry was randomly assigned to either the left or the right key on each trial (Stubbs & Pliskoff, 1969), with the restriction that three out of every six cycles were assigned to each key. An interval was sampled randomly without replacement from a list associated with the assigned key at the start of a trial. Separate lists were maintained for cycles in which entry into the left and right terminal links was arranged so that each interval was used equally often on left- and right-assigned trials. The

intervals constituting the VI 15-s schedules contained the first 12 intervals from an arithmetic progression,  $a, 3a, 5a, \dots$ , in which  $a$  equals one twelfth of the schedule value. The initial-link VI timer began timing after the first response to either key. There was no changeover delay. When the selected interval of the VI schedule had timed out, the next response to the assigned key resulted in terminal-link entry. For the second group of subjects, independent concurrent VI 30-s VI 30-s schedules operated during the initial links. Because both the left- and right-key intervals elapsed during initial links, the expected duration of initial links was the same as in the dependent-scheduling arrangement (15 s). These schedules also were composed of 12 intervals constructed from the same arithmetic progression and were sampled without replacement. At the start of a component, intervals were sampled from both schedules; thereafter, an interval was sampled when terminal-link entry was gained for a particular alternative. As above, both schedules began timing in a cycle after the first response to either key and there was no changeover delay. The first response to a key after its schedule had timed out produced entry into the corresponding terminal link. When either terminal link was entered, timing for both initial-link schedules stopped.

For both groups of subjects, terminal-link entry was accompanied by a change from constant to flashing illumination on the relevant key (i.e., 0.25 s off, 0.25 s on). The other key was darkened and responses to it had no scheduled consequence. Terminal links provided access to grain, or a blackout of equivalent duration, independently of responding and after a delay determined by a fixed-time (FT) schedule. Whether reinforcement or blackout occurred at the end of the delay was determined probabilistically (see below). During reinforcement, the grain magazine was raised and illuminated for 3 s.

Different pairs of terminal-link schedules were used for the left and right alternatives in each component: FT 10 s (left) and FT 20 s (right) in the red component, FT 15 s and FT 15 s in the white component, FT 20 s and FT 10 s in the green component. Thus, immediacy ratios were 2:1, 1:1, and 1:2 in the red, white, and green components respectively. These schedules remained unchanged through-

out the experiment. The same pair of reinforcer probabilities was used across components in each condition. Probability pairs in four conditions were .67 (left) and .33 (right), .33 and .67, .83 and .17, or .17 and .83; corresponding to probability ratios of 2:1, 1:2, 5:1, and 1:5. Probabilities were implemented by selecting from a list without replacement such that out of every 12 terminal links, reinforcement would be delivered 10 times (and blackout would occur twice) when the probability was .83, 8 times (with 4 blackouts) when it was .67, 4 times (with 8 blackouts) when it was .33, and 2 times (with 10 blackouts) when it was .17. The four probability ratios were used in different conditions.

Table 1 lists the conditions, including the reinforcer probabilities for left- and right-key terminal links, and whether or not the reinforcement outcome (reinforcement or nonreinforcement) was signaled during the terminal links. In both signaled and unsignaled conditions, the keylight stimulus (flashing color) was the same for each occurrence of a particular terminal link, regardless whether food or blackout occurred on that trial. However, in the signaled conditions, a flashing houselight (0.25 s on, 0.25 s off) accompanied each terminal link that ended in blackout. In these conditions, the houselight flashed in phase with the flashing keylight. In unsignaled conditions, the houselight was illuminated continuously during terminal links.

The order of conditions was counterbalanced across subjects. Thus, each subject began the experiment in a condition associated with a different probability ratio. Half the subjects experienced the four signaled conditions first and the other half experienced the four unsignaled conditions first. Training in each condition continued for between 39 and 45 sessions. Table 1 gives the positions of Conditions 1 through 8 in each subject's sequence of conditions, along with the number of training sessions given. A formal stability criterion was not employed because in prior studies using multiple concurrent chains, this amount of training was sufficient for response allocation to stabilize. However, after completing the experiment we applied a commonly used stability criterion retrospectively to initial-link response allocation in each condition (see

Table 1

Reinforcer probabilities for the left and right keys, and the presence or absence of signaling in each condition of the experiment.

Condition	Signal	Reinforcer probabilities		Dependent scheduling group				Independent scheduling group			
		Left Key	Right key	161	162	163	164	185	186	187	188
1	present	0.67	0.33	1 (39)	6 (39)	3 (39)	8 (39)	1 (40)	6 (40)	3 (40)	8 (40)
2	present	0.33	0.67	2 (40)	5 (40)	4 (40)	7 (40)	2 (45)	5 (45)	4 (45)	7 (45)
3	present	0.83	0.17	3 (40)	8 (40)	1 (40)	6 (40)	3 (41)	8 (41)	1 (41)	6 (41)
4	present	0.17	0.83	4 (40)	7 (40)	2 (40)	5 (40)	4 (41)	7 (41)	2 (41)	5 (41)
5	absent	0.67	0.33	5 (40)	2 (40)	7 (40)	4 (40)	5 (41)	2 (41)	7 (41)	4 (41)
6	absent	0.33	0.67	6 (40)	1 (40)	8 (40)	3 (40)	6 (41)	1 (41)	8 (41)	3 (41)
7	absent	0.83	0.17	7 (40)	4 (40)	5 (40)	2 (40)	7 (40)	4 (40)	5 (40)	2 (40)
8	absent	0.17	0.83	8 (40)	3 (40)	6 (40)	1 (40)	8 (40)	3 (40)	6 (40)	1 (40)

*Note.* The position of each condition in subjects' sequences of conditions is given for Pigeons 161 through 164 in the dependent scheduling group and for Pigeons 185 through 188 in the independent scheduling group, with the number of sessions of training in parentheses. The listed reinforcer probabilities for left and right keys were used in all three components in each condition.

below). We concluded that trends at the end of training were rare, and that where they existed they did not undermine our major conclusions.

All significance tests used the .05 level.

## RESULTS

The numbers of responses, terminal-link entries, and reinforcers were aggregated over the last 10 sessions for each component in each condition. The raw data are given in the Appendix, and were used in all subsequent data analysis. Log initial-link response ratios (left/right) were analyzed using the following logarithmic form of the generalized matching law, which includes a term for relative reinforcer probability ( $P$ ):

$$\log \frac{B_1}{B_2} = \log c + a_R \log \left( \frac{R_1}{R_2} \right) + a_D \log \left( \frac{1/D_1}{1/D_2} \right) + a_P \log \left( \frac{P_1}{P_2} \right) \quad (2)$$

For subjects in the dependent-scheduling group the two terminal links were entered equally often, with few and minor exceptions (see Appendix), and so  $\log(R_1/R_2)$  in Equation 2 was assumed to be 0.

### *Sensitivity to Relative Probability of Reinforcement*

Figures 1 and 2 show data from individual subjects in the dependent-scheduling group, Pigeons 161 through 164, in the unsignaled

and signaled conditions respectively. Figure 1 shows the base-10 logarithms of initial-link response ratios (left key/right key) as a function of log reinforcer probability ratios, in the unsignaled conditions, for the 4 subjects. Data from the three components are shown by different symbols, and the equations of least-squares regression lines fitted to each component's data are given in the figure. As is evident in Figure 1, all subjects showed high levels of sensitivity to relative reinforcer probability (high regression slopes) in each component when the terminal links were unsignaled. Individual sensitivity values, averaged across components, were 1.75, 2.19, 2.46 and 1.70, for Pigeons 161, 162, 163 and 164, respectively. The overall mean was 2.02.

Figure 2 shows log initial-link response ratios as a function of log reinforcer probability ratio in the signaled conditions for the same 4 subjects. Individual sensitivity values averaged across components were 1.30, 1.23, 1.70 and 1.48 for Pigeons 161, 162, 163 and 164, respectively, with an overall mean of 1.43. Overall, sensitivity was 29% lower in these conditions, exemplifying the signaling effect. Specifically, sensitivity values were lower in signaled relative to unsignaled conditions in every component for every subject, and this difference was significant on a Wilcoxon matched-pairs signed-ranks test,  $z = 3.51$ ,  $p < .05$ .

In addition to the main signaling effect, there also appeared to be a reduction in sensitivity to relative reinforcer immediacy in



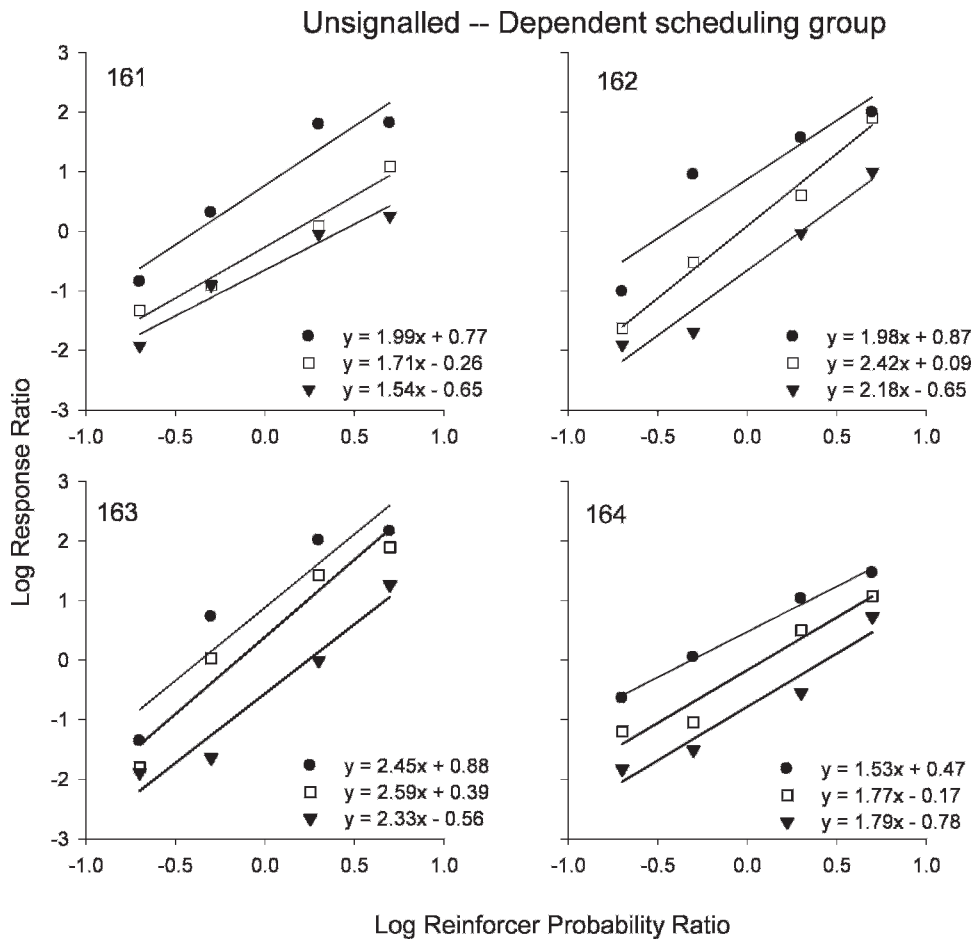


Fig. 1. Log<sub>10</sub> initial-link response ratios (left/right) are plotted against log<sub>10</sub> reinforcer probability ratios in the unsignalled conditions, for subjects in the independent scheduling group. Equations of least-squares regression lines are shown for each subject for the red, white, and green components, separately and in that order. Filled circles represent data from red components, unfilled squares represent data from white components, and filled triangles represent data from green components.

the signalled conditions. Sensitivity to relative immediacy appears as the vertical distance between the regression lines for individual components in Figures 1 and 2, measured by the intercept values of the fitted regression lines. In both figures, regression lines for the red component have positive intercept values, those for the white component have intercept values close to 0 (on average,  $-0.03$ ), and those in the green component have negative intercept values. The range over which intercept values varied indicates the degree to which relative immediacy controlled response allocation, and appears generally to be smaller in signalled than in unsignalled conditions.

Figures 3 and 4 repeat the above analyses for the subjects in the independent scheduling group, and confirm both of the main results reported above. Figure 3 shows log initial-link response ratios as a function of log probability ratios in the unsignalled conditions for the 4 subjects. Again, all subjects displayed high levels of sensitivity to relative probability in each component when the terminal links were unsignalled. Sensitivity values varied across components for individual subjects, but the variation appears unsystematic. Individual sensitivity values, averaged across components, were 1.67, 2.28, 1.79 and 1.77 for Pigeons 185, 186, 187 and 188, respectively, with an overall mean of 1.88.

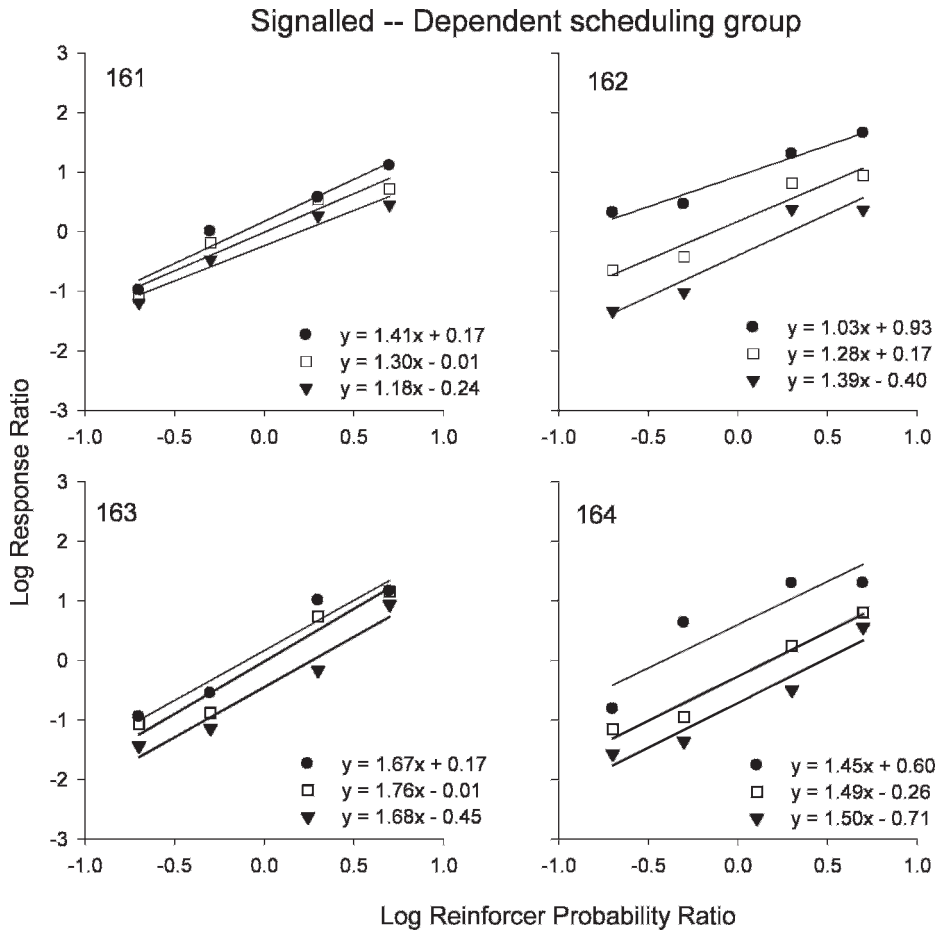


Fig. 2.  $\log_{10}$  initial link response ratios (left/right) are plotted against  $\log_{10}$  reinforcer probability ratios in the signaled conditions, for subjects in the independent-scheduling group. Equations of least-squares regression lines are shown for each subject for the red, white, and green components, separately and in that order. Filled circles represent data from red components, unfilled squares represent data from white components, and filled triangles represent data from green components.

Figure 4 shows the log initial-link response ratio as a function of the log probability ratio in the signaled conditions for the same 4 subjects. Response allocation for all subjects was sensitive to relative reinforcer probability in each component when the terminal links were signaled, and sensitivity values were comparable across components. Individual subjects' sensitivity values, averaged across components, were 0.69, 1.26, 1.76 and 1.53 for Pigeons 185, 186, 187 and 188, respectively, with an overall mean of 1.31. As with the dependent-scheduling group, the sensitivity values were substantially lower in the signaled conditions relative to the unsignaled conditions. This difference was found in 9 out of 12

individual comparisons (Wilcoxon matched-pairs signed-ranks test;  $z = 2.35$ ,  $p < .05$ ). As for the dependent-scheduling group, the intercepts of regression lines, which reflect control of response allocation by relative immediacy of reinforcement, varied across components. Comparing the range over which they varied for unsignaled conditions (Figure 3) and signaled conditions (Figure 4), it appears that the degree of control was higher in the unsignaled conditions.

A possible complication in the case of the independent scheduling group was that sensitivity values may partly reflect sensitivity to relative terminal-link entry ratios, which are free to vary with changes in subjects'

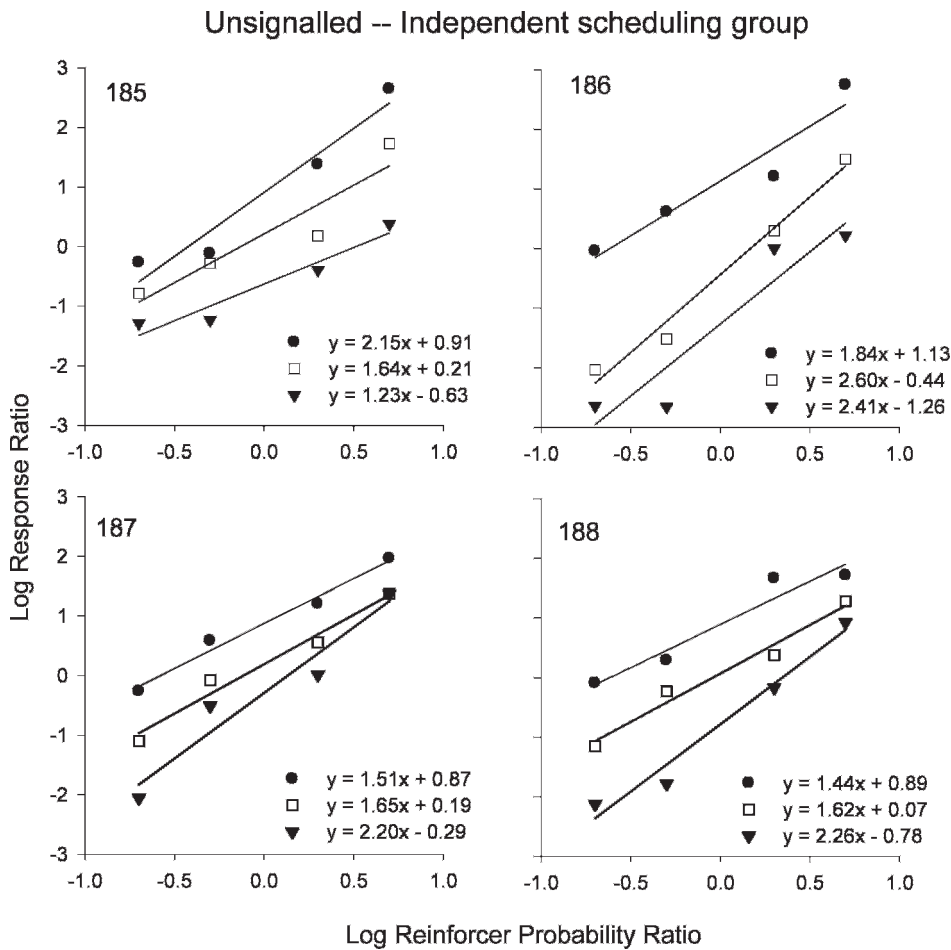


Fig. 3.  $\text{Log}_{10}$  initial link response ratios (left/right) are plotted against  $\text{log}_{10}$  reinforcer probability ratios in the unsignalled conditions, for subjects in the dependent-scheduling group. Equations of least-squares regression lines are shown for each subject for the red, white, and green components, separately and in that order. Filled circles represent data from red components, unfilled squares represent data from white components, and filled triangles represent data from green components.

preference in this procedure. To assess whether the difference in sensitivity between signaled and unsignalled conditions remained when sensitivity of initial-link response ratios to relative terminal-link entry rates was accounted for, we re-estimated  $a_p$  using Equation 2. Specifically, we entered the obtained entry rates as  $R_1$  and  $R_2$ , and fixed  $a_R$  at 1.0. Because relative immediacy of reinforcement was constant within components, we fixed  $a_D$  (at 0) and let the constant  $\log c$  account for the effects of relative reinforcer immediacy in different components. Values for  $a_p$  and  $\log c$  are given in Table 2, separately for the three components and for signaled and unsignalled

conditions. Values for  $a_p$  were greater in unsignalled conditions in 11 out of 12 cases, an even stronger result than is seen in Figures 3 and 4. The single exception, Bird 187 in the red component, gave sensitivity values of 1.08 in the signaled condition and 1.00 in the unsignalled condition. In all other cases, the sensitivity values differed by 0.10 or more and overall, sensitivity was lower in signaled conditions by 27%.

*Sensitivity to Relative Immediacy of Reinforcement*

Inspection of intercept values in Figures 1 through 4 suggested that the effect of signaling reinforcement and nonreinforcement on



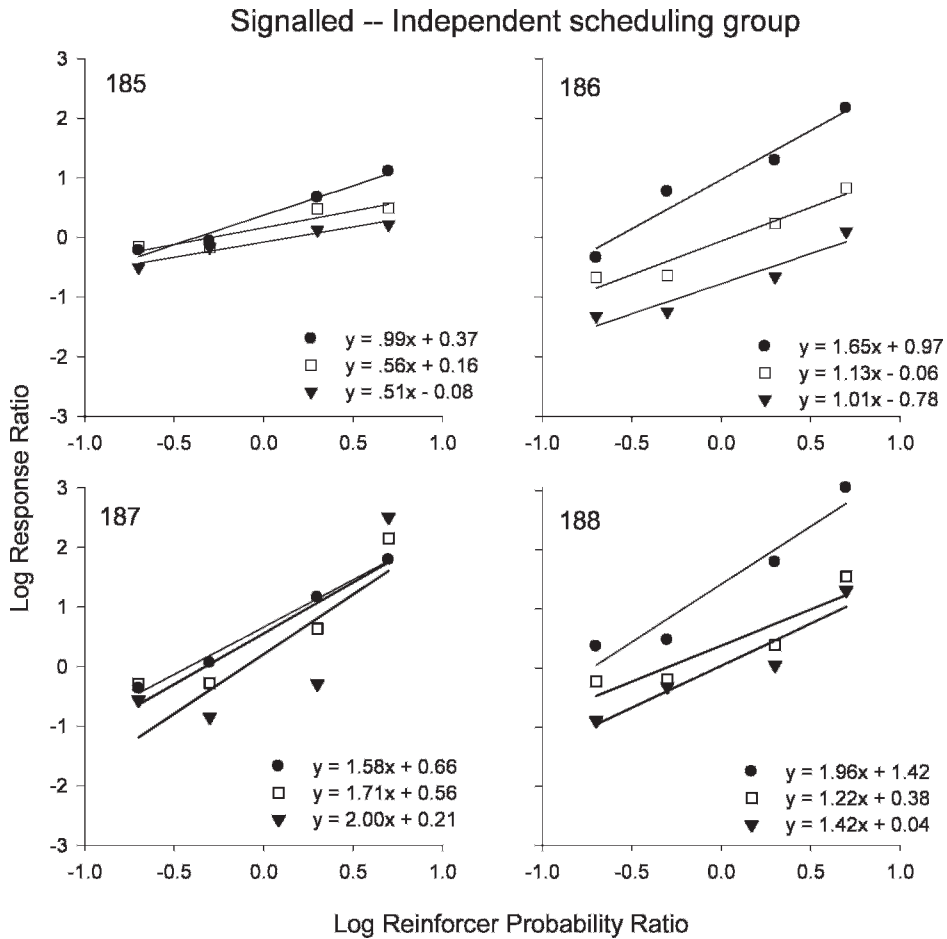


Fig. 4.  $\log_{10}$  initial link response ratios (left/right) plotted against  $\log_{10}$  reinforcer probability ratios in the signalled conditions, for subjects in the dependent-scheduling group. Equations of least-squares regression lines are shown for each subject for the red, white, and green components, separately and in that order. Filled circles represent data from red components, unfilled squares represent data from white components, and filled triangles represent data from green components.

individual trials was not limited to sensitivity to relative reinforcer probability, and that sensitivity to relative immediacy was also reduced. We conducted further analysis of sensitivity to immediacy, regressing log initial-link response ratios on log immediacy ratios, separately for each of the four log probability ratios and for signalled and unsignalled conditions. Individual results for the 4 subjects in the independent-scheduling group were obtained by fitting Equation 2, using obtained rates of terminal-link entry for  $R_1$  and  $R_2$ . As before, the  $a_R$  parameter was fixed at 1.0 and the  $a_P$  parameter was fixed at 0, letting the constant log  $c$  account for the effects of reinforcer

probability across conditions. The results are given in Table 3.

With few exceptions, the fits were satisfactory. Equation 2 accounted for 85% or more of the (log ratio) variance in preference in 57 out of 64 cases. The mean values for  $a_D$  for the dependent-scheduling group were 2.35 in the unsignalled conditions, and 1.52 (35% lower) in the signalled conditions (Wilcoxon test,  $z = 2.33$ ,  $p < .05$ ). For the 4 subjects in the independent-scheduling group, the mean values for  $a_D$  were 1.64 in the unsignalled conditions and 1.15 (30% lower) in the signalled conditions, and again the difference was statistically significant (Wilcoxon test,  $z =$

Table 2  
Parameter values from fits of Equation 2 to initial-link log response ratios in the three components.

		Red Component			White Component			Green Component		
Pigeon		$a_P$	$\log c$	VAC	$a_P$	$\log c$	VAC	$a_P$	$\log c$	VAC
185	Unsignaled	1.20	0.46	.98	1.10	0.09	.97	0.80	−0.37	.96
	Signaled	0.84	0.30	.98	0.54	0.15	.92	0.46	−0.05	.95
186	Unsignaled	1.14	0.79	.96	1.62	−0.16	.97	0.85	−0.40	.97
	Signaled	1.03	0.62	.99	0.86	0.05	.98	0.67	−0.43	.92
187	Unsignaled	1.00	0.62	.99	1.27	0.12	.98	1.51	−0.20	.93
	Signaled	1.08	0.45	.97	1.03	0.30	.99	0.98	−0.14	.98
188	Unsignaled	1.04	0.67	.99	1.25	0.11	.91	1.47	−0.46	.93
	Signaled	0.82	0.82	.96	1.00	0.32	.99	1.16	0.04	.98

*Note.* Analyses used obtained terminal-link entry rates with  $a_R$  fixed at 1.0, ratios of arranged reinforcer probabilities, and  $a_D$  fixed at zero. The proportion of variance accounted for by the fit (VAC) is also given. (Data from the independent-scheduling group.)

2.77,  $p < .05$ ). Across the 8 subjects in two groups, greater sensitivity to immediacy in unsignaled than in signaled conditions was found in 24 out of 32 comparisons, confirming an effect of signaling on sensitivity of initial-link response ratios to relative immediacy of reinforcement.

In the analyses presented above we accounted for variations in relative terminal-link entry rate for the independent-scheduling group by fitting Equation 2 using obtained terminal-link

entry rates for  $R_1$  and  $R_2$ , with  $a_R$  fixed at 1.0. It is possible that different conclusions might be reached if  $a_R$  was higher or lower than this. Accordingly, we reassessed the effect of unequal terminal link entry in further analyses which varied  $a_R$  upwards from 0.5 in steps of 0.15, and asked whether the signaling effect remained as  $a_R$  increased. The results of these analyses were that sensitivity to relative immediacy remained significantly greater ( $p < .05$  on a Wilcoxon test) in unsignaled conditions

Table 3  
Fitted values for  $a_D$  and  $\log c$  (Equation 2) for each pigeon and each log reinforcer probability ratio in the unsignaled and signaled conditions.

		Log reinforcer probability ratio											
		−0.69			−0.3			0.3			0.69		
Pigeon		$a_D$	$\log c$	VAC	$a_D$	$\log c$	VAC	$a_D$	$\log c$	VAC	$a_D$	$\log c$	VAC
<i>Dependent-scheduling group</i>													
161	Unsignaled	1.78	−1.36	1.00	2.02	−0.50	.75	3.04	0.61	.80	2.59	1.05	1.00
	Signaled	0.35	−1.10	.98	0.78	−0.22	.99	0.50	0.46	.83	1.09	0.76	.99
162	Unsignaled	1.48	−1.52	.96	4.38	−0.42	1.00	2.65	0.72	.99	1.65	1.63	.82
	Signaled	2.73	−0.56	.99	2.44	−0.33	.99	1.54	0.83	1.00	2.13	0.99	1.00
163	Unsignaled	0.87	−1.68	.87	3.93	−0.29	.95	3.34	1.14	.94	1.47	1.77	.95
	Signaled	0.80	−1.15	.92	0.98	−0.85	.99	1.93	0.53	.91	0.36	1.08	.77
164	Unsignaled	1.97	−1.22	1.00	2.57	−0.83	.95	2.62	0.33	.97	1.21	1.09	1.00
	Signaled	1.24	−1.18	1.00	3.29	−0.55	.89	2.96	0.35	.99	1.22	0.89	.96
<i>Independent-scheduling group</i>													
185	Unsignaled	0.95	−0.55	1.00	0.90	−0.36	.98	2.16	0.29	.99	1.48	0.87	.98
	Signaled	0.39	−0.27	.74	0.07	−0.11	.86	0.78	0.39	.99	1.11	0.52	1.00
186	Unsignaled	0.86	−0.57	.90	3.06	−0.55	.96	1.72	0.44	.94	2.26	0.98	1.00
	Signaled	0.95	−0.53	.97	1.96	−0.11	.97	2.19	0.26	1.00	1.84	0.70	1.00
187	Unsignaled	1.84	−0.80	1.00	1.54	−0.02	.99	1.63	0.51	1.00	0.41	1.03	.96
	Signaled	0.33	−0.33	.65	1.31	−0.30	.98	1.96	0.39	.98	0.31	1.06	.97
188	Unsignaled	2.05	−0.70	.99	2.27	−0.35	.98	2.33	0.50	.99	0.82	0.99	.99
	Signaled	1.69	−0.18	1.00	1.16	0.01	.89	1.86	0.53	.98	0.48	1.22	1.00

*Note.* The proportion of variance accounted for (VAC) is given for each fit. Analyses for subjects in the independent-scheduling group used obtained log terminal-link entry ratios, with  $a_R$  fixed at 1.0.

Table 4

Parameter estimates and proportion of variance accounted for by the concatenated generalized-matching model (Equation 2) when fitted to the data from individual pigeons.

	Pigeon	$\log c$	$a_P$ (unsig)	$a_P$ (sig)	$a_D$ (unsig)	$a_D$ (sig)	VAC
Independent	185	0.10	1.03	0.62	1.37	0.59	0.97
	186	0.08	1.20	0.85	1.97	1.73	0.96
	187	0.19	1.25	1.03	1.35	0.98	0.96
	188	0.25	1.25	0.99	1.87	1.30	0.96
	Average	0.15	1.18	0.87	1.64	1.15	0.96
Dependent	161	-0.04	1.76	1.31	2.38	0.68	0.94
	162	0.17	2.22	1.25	2.52	2.20	0.94
	163	0.07	2.48	1.73	2.41	1.00	0.92
	164	-0.14	1.72	1.49	2.09	2.18	0.94
	Average	0.01	2.05	1.44	2.35	1.52	0.94

Note. Results are shown separately for the groups with independent and dependent initial-link schedules.

up to a value of  $a_R = 1.4$ . At this value and above, fitted values for  $a_D$  sometimes became substantially negative, which seems implausible. Overall, this analysis shows that the effect of signaling on sensitivity to relative reinforcer immediacy was robust to substantial variation in  $a_R$ .

To provide an economical description of the data in terms of the generalized matching law, a version of Equation 2 with separate sensitivity parameters ( $a_D$  and  $a_P$ ) for signaled and unsignaled conditions was fitted to the individual data. For the independent-schedules group, the value of  $a_R$  was set equal to 1. For each pigeon, there were five parameters estimated from 24 data points. Table 4 gives the results for individual pigeons, and Figure 5 shows the average bias and sensitivity

parameters separately for group and signaling condition. The generalized-matching model provided a good description of the data, accounting for an average of 96% and 94% of the variance for the independent and dependent groups, respectively. Sensitivity to probability ( $a_P$ ) was higher in the unsignaled condition for both groups (means = 1.19 and 0.87, and 2.05 and 1.45, respectively for independent and dependent scheduling), as was sensitivity to immediacy (means = 1.64 and 1.15, and 2.35 and 1.52). An ANOVA on the sensitivity parameters, with variable (probability vs. immediacy), signaling condition and group as factors, found a significant effect of signaling condition,  $F(1,6) = 20.28$ ,  $p < .05$ , confirming that sensitivity to both probability and immediacy was greater in the unsignaled condition. The effect of group was also significant,  $F(1,6) = 14.88$ ,  $p < .05$ , indicating that sensitivity was greater for the dependent group. Neither the main effect of variable nor any of the interactions was significant.

### Independence of Probability and Immediacy?

Figure 6 shows the average results for both groups in the signaled and unsignaled conditions. To confirm the findings reported above and to provide a formal test of a possible interaction between immediacy and probability, we conducted a 2 (Group)  $\times$  4 (Log Probability Ratio)  $\times$  3 (Log Immediacy ratio)  $\times$  2 (signaled/unsignaled) repeated-measures ANOVA. The main effects of probability and immediacy ratios were both significant,  $F(3,18) = 240.30$ , and  $F(2,12) = 58.25$ , respectively,  $p < .05$ . The signaling effects reported above were supported by interactions of

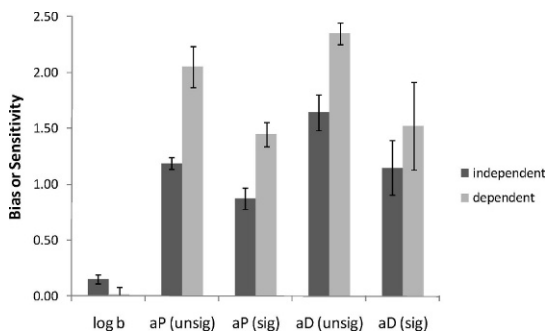


Fig. 5. Average sensitivities to delay ( $a_D$ ) and probability ( $a_P$ ) for signaled and unsignaled conditions, and bias ( $\log b$ ), estimated from fits of the generalized-matching model (Equation 2) to data from individual pigeons. Results for the independent and dependent scheduling group are shown by dark and light gray columns, respectively. Error bars indicate  $\pm 1$  SE.

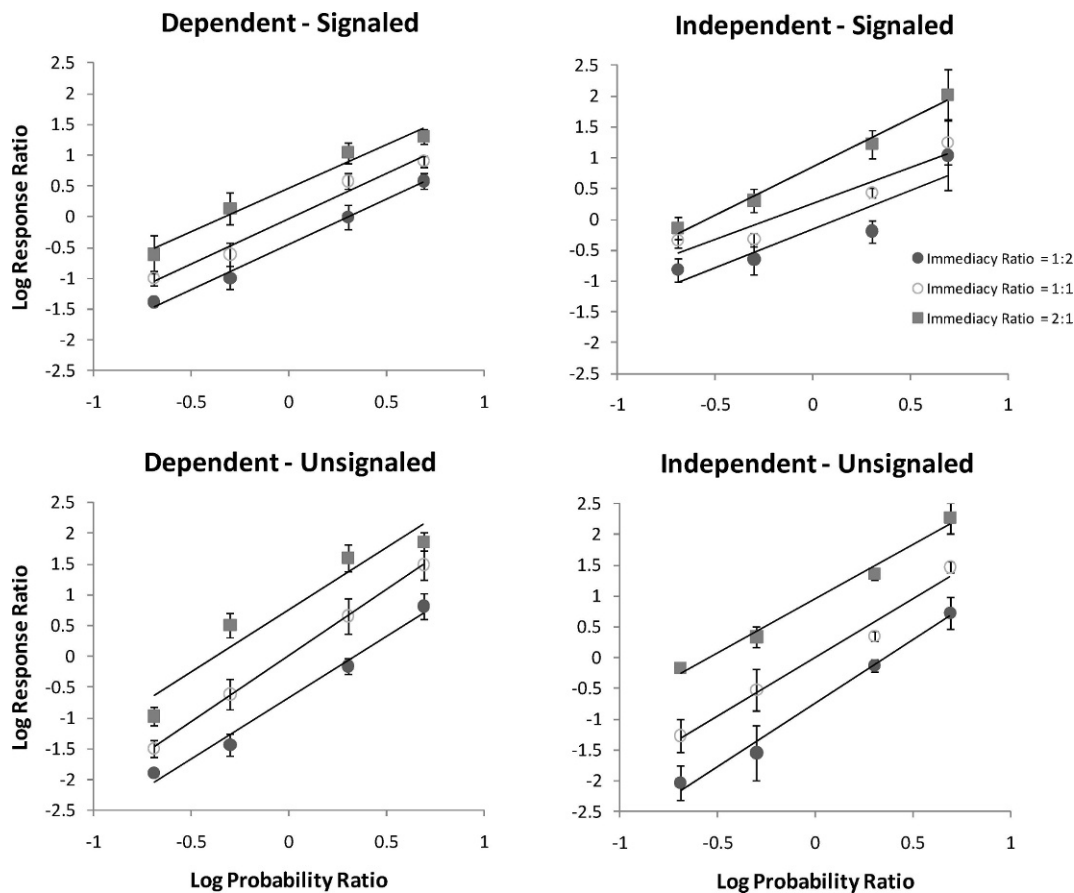


Fig. 6. Average log response ratios plotted as a function of log probability ratios (upper panels) and log immediacy ratios (lower panels). Results for shown separately for dependent and independent scheduling groups, and for unsignaled and signaled conditions. Error bars indicate  $\pm 1$  SE.

signaling condition with log probability ratio,  $F(3,18) = 6.28$ ,  $p < .05$ , and with log immediacy ratio,  $F(2,12) = 10.40$ ,  $p < .05$ . There was also a significant interaction between group and log probability ratio, consistent with the greater sensitivity to probability ratios in the dependent-scheduling group than in the independent-scheduling group, seen in Figures 1–4,  $F(3,18) = 3.17$ ,  $p < .05$ . The interaction between probability and immediacy was not significant,  $F(6,36) = 1.78$ ,  $p = .13$ . None of the other main effects or interactions was significant.

Although the lack of a significant interaction suggests that the effects of probability and immediacy ratios on choice are independent, visual inspection of Figure 6 suggests that the effect of immediacy ratios was greater at moderate than extreme probability ratios,

particularly for the dependent-schedules group. We ran separate ANOVAs for the two groups and found that the probability  $\times$  immediacy interaction was significant for the dependent-schedules group  $F(6,18) = 3.53$ ,  $p < .05$ , but not for the independent-schedules group,  $F(6,18) = 0.23$ ,  $p = .96$ . Analysis of simple effects for the dependent-schedules group found that the probability  $\times$  immediacy interaction was significant for the unsignaled condition ( $p < .05$ ), but not the signaled condition ( $p = .46$ ).

An interaction effect of the type described above might result if there was a ceiling effect on response allocation. For example, the requirement that the terminal links are entered equally often (dependent scheduling) places a lower bound on response rate to the less-preferred key in the initial link, and

potentially, a constraint on response ratios. Consistent with this interpretation, the interaction was only significant for the dependent-schedules group (when log response ratios were analyzed). To explore this possibility, Figure 7 shows obtained log response allocation as a function of predictions by the generalized-matching model (Equation 2). To generate this figure, results for individuals were pooled. The solid line in each panel is the line of equality ( $y = x$ ) so that systematic deviations in predictions can be observed. Figure 7 shows that results for the dependent group unsignaled condition (lower right panel) reveal the interaction between probability and immediacy as a clear sigmoidal pattern that is consistent with a ceiling on maximum response allocation at approximately 2 log units (i.e., 100:1). Results for the dependent group signaled condition (upper right panel) show a similar trend, but not as pronounced. By contrast, results for the independent group (left panels) indicate no systematic deviation from prediction.

Overall, these results suggest that the reduction in sensitivity to immediacy at extreme probability ratios for the dependent schedules group—and hence the interaction between probability and immediacy—may have been caused by a ceiling effect on response allocation. The unsignaled condition showed the clearest evidence of this effect, which is reasonable because it generated the more extreme preference. However, there is some ambiguity because the three-way interaction (probability  $\times$  immediacy  $\times$  signaling) was not significant, suggesting that the differences between the separate two-way interactions for the signaled and unsignaled conditions were not significant.

### *Stability*

Finally, because no formal stability criterion was used during the experiment we assessed performance over sessions in each condition to check that it met a commonly used criterion for stability. The criterion was that the median response proportion over five sessions was within .05 of the median of the previous five sessions, met five times (not necessarily consecutively) during training. Of 192 performances (8 birds  $\times$  3 delay ratios  $\times$  4 probability ratios  $\times$  2 signaling conditions), only 6 failed to meet this criterion during

training. In each of these cases, we then calculated average response proportions in five-session blocks and inspected these visually for trends over the last four blocks. Trends over blocks were suspected in four cases, all were in unsignaled conditions and all suggested increasing responding to the left key. Three of these cases were Birds 186 in Component 1 (FT 10 FT 20) of Conditions 5 and 8, and Bird 162 in Component 1 of Condition 6. The fourth case was Bird 185 in Component 3 (FT 15 FT 15). These trends imply that sensitivity to delay may be slightly greater in unsignaled conditions than is reported above, since preference for the shorter delay may have been still increasing. Since our major result is that sensitivity is greater when reinforcement outcomes are unsignaled, these trends do not undermine our conclusions. For probability, trends imply that sensitivity may be a little lower than is reported above for Birds 185 and 162 in unsignaled conditions. However, because the affected conditions involved moderate probability ratios (1:2 or 2:1), lower preference in these conditions would have little effect on sensitivity estimates overall. Thus, we conclude that our subjects' performances were sufficiently stable to support our major conclusions.

## DISCUSSION

The primary goals of the present study were to characterize the effects on choice of variation in reinforcer immediacy and probability in terms of the generalized matching law, to determine if their effects were additive and independent, and to compare results depending on whether terminal-link outcomes (i.e., reinforcement or blackout) were signaled. We trained 8 pigeons in a three-component concurrent-chains procedure in which the terminal links were FT schedules which varied across components (2:1, 1:1, and 1:2 immediacy ratios) while the reinforcer probabilities were varied across conditions. There were two groups ( $n = 4$ ) which differed in terms of whether independent or dependent VI schedules were used for the initial links. Results showed that the generalized matching law (Equation 2) provided an excellent description of the data, accounting for an average of 92% of the variance in response allocation overall. Sensitivity to reinforcer probability and

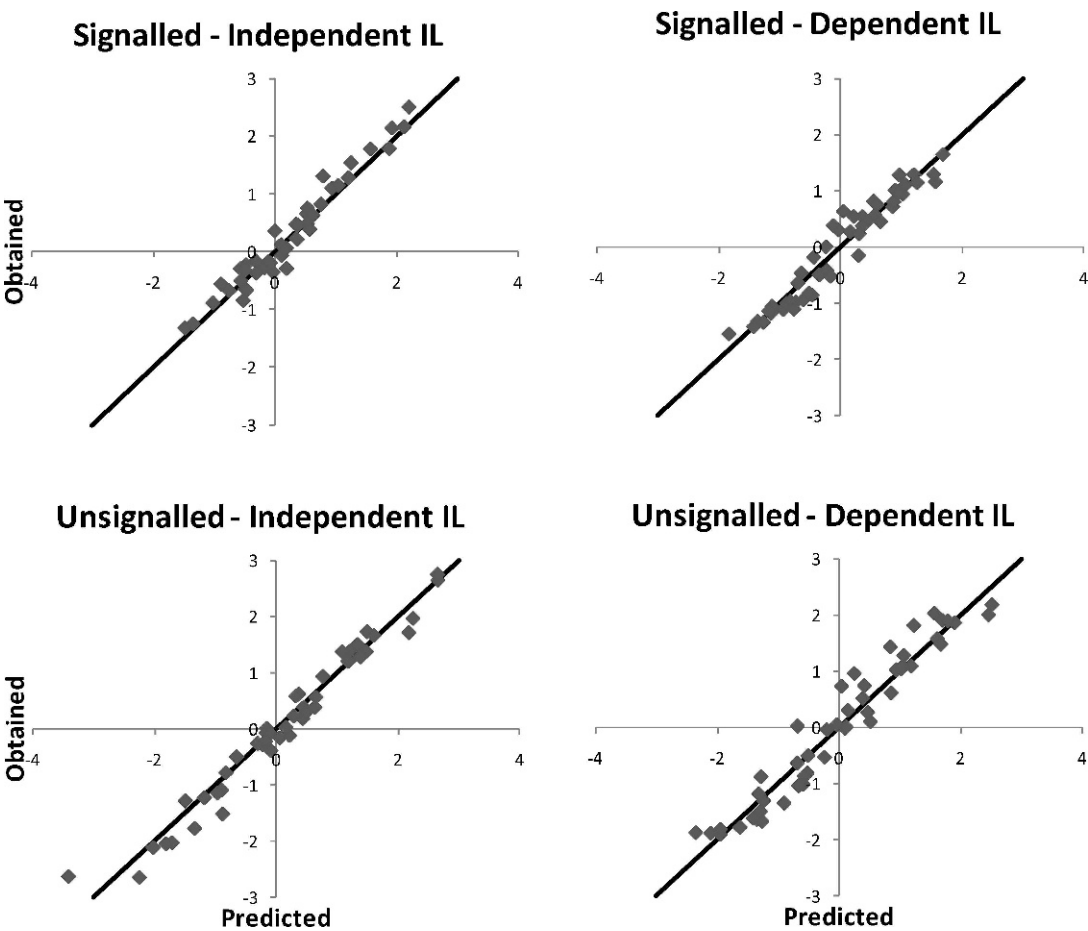


Fig. 7. Scatterplots of obtained versus predicted log response ratios based on fits of the generalized matching model (Equation 2) to data from individual pigeons. Results are shown separately for the independent-scheduling group (left panels), dependent-scheduling group (right panels), signaled condition (upper panels), and unsignaled condition (lower panels).

immediacy were both greater in the unsignalled conditions, suggesting that the effect of signaling terminal-link outcomes may not be specific to probability but may affect terminal-link reinforcer variables in general.

Another goal was to investigate the assumption of the generalized matching law that different reinforcer variables have additive and independent effects on choice. We tested whether effects of probability and immediacy on choice were independent with an ANOVA (cf. Elliffe *et al.*, 2008). Consistent with the independence assumption, the interaction was not significant in the overall ANOVA. However, visual inspection (see Figure 6) suggested

that sensitivity to immediacy was greater at moderate rather than extreme probability ratios for the dependent-schedules group. This observation was supported by an analysis of simple effects which showed that the probability  $\times$  immediacy interaction was significant for the dependent-schedules group but not the independent-schedules group. Scatterplots of predictions of the generalized-matching model versus obtained data (Figure 7) showed evidence of a possible ceiling effect in response allocation for the dependent-scheduling group in the unsignaled condition at approximately 2 log units. This effect would be expected to have a greater



impact at extreme rather than moderate probability ratios, and thus could have produced the interaction for the dependent-schedules group. In that case, the interaction might not represent failure of a key matching-law assumption, but be attributed to a procedural artefact. Sigmoidal relationships between log response and log reinforcer ratios that might be attributed to ceiling effects produced by dependent scheduling have been reported before (e.g., Davison & Jones, 1995; but cf. Baum, Schwendiman & Bell, 1999), particularly in situations where several values of a given reinforcer dimension are presented within sessions (as in the present experiment) or when conditions are in effect for only one or two sessions at a time (Grace, Bragason & McLean, 2003; Grace & McLean, 2006). However, it must be acknowledged that our results were ambiguous in that the three-way interaction (probability  $\times$  immediacy  $\times$  signalling), which would have allowed us to conclude that the probability  $\times$  immediacy interaction was limited to the unsignaled condition for the dependent-schedules group, was not significant.

Although comparing results between the groups with independent and dependent initial-link scheduling was not a primary goal, it is interesting to note that sensitivity to probability and immediacy were significantly greater in the dependent-scheduling group (see Figure 5 and Table 4). This was associated with our inclusion of a term for relative terminal-link entry rate in Equation 2, which can vary with response allocation under independent but not dependent schedules. In the analyses of sensitivity by component in Figures 1 through 4, entry rate was not taken into account and, while sensitivities were higher for the dependent group, the differences were not as large and did not reach statistical significance. For example, the average sensitivity to probability in the unsignaled conditions was 2.02 for the dependent group versus 1.88 for the independent group. It remains an open question whether independent and dependent scheduling arrangements yield equivalent estimates of sensitivity to reinforcer variables.

Previous research on choice between uncertain outcomes has shown that strong preference is established for the higher reinforcer-probability alternative in standard unsignaled procedures (e.g., Spetch & Dunn, 1987), but

when outcomes (reinforcement or nonreinforcement) scheduled for each trial are signaled during terminal links, this preference is weaker. Fantino, Dunn and Meck (1979), for example, varied probability ratios over the range 1:4 to 4:1 using signaled conditions, and reported data consistent with sensitivity values in the range 0.5 to 0.8. Sometimes, preference has been found to reverse so that response allocation favors the poorer alternative (e.g., Kendall, 1974, 1985). This reversal has been found to be more common in procedures with short initial links and long terminal links (Dunn & Spetch, 1990; Kendall, 1985). Our results are consistent with this previous research, both in that strong preferences were found in unsignaled conditions for the alternative with the higher probability of reinforcement, and in that preference reduced significantly when outcomes were signaled. However, we did not find actual reversals of preference, which would be indicated by negative values of sensitivity to probability in the signaled conditions.

Of the existing studies of signaling in probabilistic reinforcement procedures, no previous study has jointly varied probability with another reinforcement variable. Our second main finding, that signaling probabilistic reinforcers also affected sensitivity to delay, was therefore novel. This result is surprising, because the steady houselight used to signal reinforcer availability at the end of a terminal link did not provide any information relevant to reinforcer delay (at least, nothing that was not already signaled by the side-key that was illuminated during the terminal link). Yet, sensitivity to immediacy was reduced from an average (across 8 birds) of 2.00 to 1.34. This reduction, 33%, was similar to the 28% reduction seen in sensitivity to probability. The finding that sensitivity to both reinforcer variables was similarly affected by signaling suggests that signaling outcomes may have a global effect on sensitivity to events in the terminal links.

Models of choice that view terminal-link stimuli as conditioned reinforcers (stimuli that acquire reinforcing strength by association with primary reinforcement) have been successful when applied to signaled procedures in past research. An explanation of the signaling effect in these terms holds that where the probability of reinforcement in the terminal link is low, stimuli that signal reinforcing outcomes (i.e., as opposed to extinction)

acquire strong conditioned reinforcement value (see Dunn & Spetch, 1990). Thus, the choice made in the initial link is between a low probability of primary reinforcement plus strong conditioned reinforcement, on the one hand, versus a higher probability of primary reinforcement plus low (or zero) conditioned reinforcement. The added conditioned reinforcement, which develops only in the signaled procedure, therefore reduces preference for the alternative with the higher probability of primary reinforcement.

Conditioned reinforcement may also explain the effect of signaling on sensitivity to relative immediacy, although not in the way described above. Two ways in which conditioned reinforcement may be included in the concatenated matching law (Equation 2) are outlined below, and explored with respect to the signaling effects reported here. First, additional conditioned reinforcement due to signaling ( $CR$ ) could function similarly to other reinforcer variables and make an independent and additive contribution to response allocation. In this case, a separate term for relative  $CR$  could be included in Equation 2 as follows:

$$\begin{aligned} \log \frac{B_1}{B_2} = & \log c + a_R \log \left( \frac{R_1}{R_2} \right) + a_D \log \left( \frac{1/D_1}{1/D_2} \right) \\ & + a_M \log \left( \frac{M_1}{M_2} \right) + a_P \log \left( \frac{P_1}{P_2} \right) \\ & + a_{CR} \log \left( \frac{CR_1}{CR_2} \right) \end{aligned} \quad (3)$$

It is not known how  $CR_1$  and  $CR_2$  may be computed, but if conditioned reinforcement for an alternative is inversely related to the probability of primary reinforcement ( $P_1$  or  $P_2$ ), as was suggested by Spetch and Dunn (1987), then the last two log ratios must be inversely related to one another and their summation predicts the reduction in sensitivity to relative probability ( $a_P$ ) that occurs when trial outcomes are signaled. The secondary effect of signaling is not so easily accommodated, however. To predict a reduction in sensitivity to relative immediacy of reinforcement,  $CR$  must similarly be inversely related to reinforcer immediacy (i.e., positively related to delay), which seems implausible.

A second approach assumes that conditioned reinforcement is added to the value of each alternative, where value is determined by

the product of the terminal-link variables (i.e., immediacy, magnitude, and probability). If rates of entry to the two terminal links are equal, the resulting model is:

$$\log \frac{B_1}{B_2} = \log c + a_R \log \frac{R_1}{R_2} + \log \left[ \frac{V_1 + CR_1}{V_2 + CR_2} \right], \quad (4)$$

$$\text{where } V = (1/D)^{a_D} \cdot M^{a_M} \cdot P^{a_P}$$

Again, if conditioned reinforcement is an inverse function of reinforcer probability, the addition of  $CR_1$  and  $CR_2$  to terminal-link value moves response ratios towards indifference, so Equation 4 models the signaling effect. Because neither log immediacy ratios nor log probability ratios are affected, the slopes of lines relating  $\log (B_1/B_2)$  to both of these reinforcement variables must be reduced. That is, the assumptions embodied in Equation 4 can predict the reduction in sensitivity to both immediacy and probability of reinforcement when outcomes are signaled. In fact, sensitivities to both immediacy and probability are reduced even if  $CR_1 = CR_2$ , so Equation 4 is consistent with the ordinal effects in the present data across a wide range of assumed relative values for  $CR_1$  and  $CR_2$ .

Equation 4 can be extended to a version of Grace's (1994) Contextual Choice Model if the rightmost term (i.e., log value ratio) is multiplied by  $T_i/T_j$ . This results in a prediction that  $T_i/T_j$  should modulate sensitivity to reinforcer immediacy and probability similarly in unsignaled and signaled conditions. The effects of varying initial- and terminal-link durations in unsignaled conditions are reasonably consistent with the above prediction (Spetch & Dunn, 1987; Experiment 2) but in signaled conditions, their effects appear to be inconsistent with it (Kendall, 1974; 1985; Dunn & Spetch, 1990). Kendall (1974; 1985) reported data suggesting decreases in preference for the higher-probability alternative as terminal-link delay increased, and increases as the durations of initial links increased. These changes are the reverse of the usual effects observed in unsignaled conditions (Spetch & Dunn). Dunn and Spetch found no clear effect of varying initial- or terminal-link durations in signaled conditions in their Experiment 1. In their Experiment 2, they found increasing preference with increasing terminal-link duration in unsignaled conditions, and again, no effect of terminal-link

duration in signaled conditions. In their Experiment 3, they found an increase in preference as initial-link durations increased from 0 to 10 s in signaled conditions, but no effect of further variation up to 40 s. Thus, only data from their Experiment 3 suggest an effect in signaled conditions, and overall, existing data suggest that in signaled conditions preference is not reliably affected by temporal context.

A second expectation that derives from Equation 4 is that the secondary effect of signaling will only be found with sensitivity to terminal-link variables. More specifically, sensitivity to relative rate of terminal-link entry should be unaffected by signaling trial outcomes when reinforcement in terminal links is uncertain. This prediction, in contrast with the secondary effects of signaling on sensitivity to relative delay in the present study, comes about because Equation 4 assumes that conditioned reinforcement is added to terminal-link value. One way to assess the validity of Equation 4 may, therefore, be to study the effects of initial- and terminal-link determiners of preference under signaled and unsignaled conditions.

To conclude, we used a flashing houselight to signal outcomes in terminal links with probabilistic reinforcement, and found that signaling probabilistic reinforcers reduced sensitivity of choice to relative probability of reinforcement, in accord with previous data. We also report a new effect, namely, that the same signaling reduced sensitivity of choice to relative immediacy of reinforcement, which we varied parametrically with relative probability. We showed that both of these effects of signaling can be modeled by incorporating conditioned reinforcement into the matching law, such that the value of each terminal link is determined, conditioned reinforcement is added, and the ratio of sums determines initial-link preference. A full evaluation of this approach must await data on the effects of signaling on sensitivity to relative rate of terminal-link entry, and on sensitivity to other terminal-link reinforcer variables.

## REFERENCES

- Autor, S. M. (1969). The strength of conditioned reinforcers as a function of frequency and probability of reinforcement. In D. P. Hendry (Ed.), *Conditioned reinforcement* (pp. 127–162). Homewood, IL: Dorsey Press.
- Baum, W. M. (1974). On two types of deviation from the matching law: bias and undermatching. *Journal of the Experimental Analysis of Behavior*, 22, 231–242.
- Baum, W. M., Schwendiman, J. W., & Bell, K. E. (1999). Choice, contingency discrimination, and foraging theory. *Journal of the Experimental Analysis of Behavior*, 71, 355–373.
- Baum, W. M., & Rachlin, H. C. (1969). Choice as time allocation. *Journal of the Experimental Analysis of Behavior*, 12, 861–874.
- Berg, M. E., & Grace, R. C. (2004). Independence of terminal-link entry rate and immediacy in concurrent chains. *Journal of the Experimental Analysis of Behavior*, 82, 235–251.
- Catania, A. C. (1963). Concurrent performances: A baseline for the study of reinforcement magnitude. *Journal of the Experimental Analysis of Behavior*, 12, 861–874.
- Chung, S. H., & Herrnstein, R. J. (1967). Choice and delay of reinforcement. *Journal of the Experimental Analysis of Behavior*, 10, 67–74.
- Davison, M. (1983). Bias and sensitivity to reinforcement in a concurrent-chains schedule. *Journal of the Experimental Analysis of Behavior*, 40, 15–34.
- Davison, M., & Jones, B. M. (1995). A quantitative analysis of extreme choice. *Journal of the Experimental Analysis of Behavior*, 64, 147–162.
- Dunn, R., & Spetch, M. L. (1990). Choice with uncertain outcomes: Conditioned reinforcement schedules. *Journal of the Experimental Analysis of Behavior*, 53, 201–218.
- Elliffe, D., Davison, M., & Landon, J. (2008). Relative reinforcer rates and magnitudes do not control concurrent choice independently. *Journal of the Experimental Analysis of Behavior*, 90, 169–185.
- Fantino, E. (1969). Choice and rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, 12, 723–730.
- Fantino, E., Dunn, R., & Meck, W. (1979). Percentage reinforcement and choice. *Journal of the Experimental Analysis of Behavior*, 32, 335–340.
- Grace, R. C. (1994). A contextual model of concurrent-chains choice. *Journal of the Experimental Analysis of Behavior*, 61, 113–129.
- Grace, R. C. (1995). Independence of delay and magnitude of reinforcement in concurrent chains. *Journal of the Experimental Analysis of Behavior*, 63, 255–276.
- Grace, R. C., Bedell, M. A., & Nevin, J. A. (2002). Preference and resistance to change with constant- and variable-duration terminal links: Effects of reinforcement rates and magnitude. *Journal of the Experimental Analysis of Behavior*, 77, 233–255.
- Grace, R. C., Bragason, O., & McLean, A. P. (2003). Rapid acquisition of preference in concurrent chains. *Journal of the Experimental Analysis of Behavior*, 80, 235–252.
- Grace, R. C., & McLean, A. P. (2006). Rapid acquisition in concurrent chains: Evidence for a decision model. *Journal of the Experimental Analysis of Behavior*, 85, 181–202.
- Herrnstein, R. J. (1961). Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, 4, 267–272.

- Herrnstein, R. J. (1964). Secondary reinforcement and rate of primary reinforcement. *Journal of the Experimental Analysis of Behavior*, 7, 27–36.
- Kendall, S. B. (1974). Preference for intermittent reinforcement. *Journal of the Experimental Analysis of Behavior*, 21, 463–473.
- Kendall, S. B. (1985). A further study of choice and percentage reinforcement. *Behavioral Processes*, 10, 399–413.
- McLean, A. P., & Blampied, N. M. (2001). Sensitivity to relative reinforcer rate in concurrent schedules: Independence from relative and absolute reinforcer duration. *Journal of the Experimental Analysis of Behavior*, 75, 25–42.
- Spetch, M. L., & Dunn, R. (1987). Choice between reliable and unreliable outcomes: Mixed percentage-reinforcement in concurrent chains. *Journal of the Experimental Analysis of Behavior*, 47, 57–72.
- Stubbs, D. A., & Pliskoff, S. S. (1969). Concurrent responding with fixed relative rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, 12, 887–895.

*Received: February 21, 2010*

*Final Acceptance: August 17, 2010*

APPENDIX

Raw data for individual subjects, aggregated over the last ten sessions of each condition.  $p(\text{Left})$ ,  $p(\text{Right})$  = terminal-link reinforcer probabilities;  $B_L, B_R$  = initial-link responses;  $e_L, e_R$  = terminal-link entries;  $r_L, r_R$  = terminal-link reinforcers;  $rt_L, rt_R$  = terminal-link response rates (10x resp/min; subscripts L and R indicate the left and right alternatives).

Dependent Scheduling Group			$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$
Condition	Component												
161	1	Red (FT 10 FT 20)	0.17	0.83	S	717	6933	84	84	14	70	167.50	253.25
	2	Red (FT 10 FT 20)	0.33	0.67	S	2523	2517	108	108	36	72	680.50	313.50
	3	Red (FT 10 FT 20)	0.67	0.33	S	5660	1522	103	102	67	34	726.50	229.75
	4	Red (FT 10 FT 20)	0.83	0.17	S	9245	722	120	120	100	20	953.50	99.50
	5	Red (FT 10 FT 20)	0.17	0.83	U	727	5106	107	112	18	92	1076.71	832.70
	6	Red (FT 10 FT 20)	0.33	0.67	U	5046	2446	107	102	36	67	1336.30	503.24
	7	Red (FT 10 FT 20)	0.67	0.33	U	10640	172	92	95	61	32	976.50	296.16
	8	Red (FT 10 FT 20)	0.83	0.17	U	10445	159	92	100	76	18	1201.00	526.62
	1	White (FT 15 FT 15)	0.17	0.83	S	529	6934	66	65	12	55	41.00	386.67
	2	White (FT 15 FT 15)	0.33	0.67	S	2116	3265	108	108	36	72	767.67	375.00
	3	White (FT 15 FT 15)	0.67	0.33	S	5960	1725	120	120	80	40	830.33	288.33
	4	White (FT 15 FT 15)	0.83	0.17	S	6739	1295	120	120	100	20	951.33	139.21
	5	White (FT 15 FT 15)	0.17	0.83	U	307	6531	102	105	17	90	624.35	1040.48
	6	White (FT 15 FT 15)	0.33	0.67	U	733	5903	109	118	39	79	868.79	650.65
	7	White (FT 15 FT 15)	0.67	0.33	U	2448	1975	86	86	58	29	1050.87	526.52
	8	White (FT 15 FT 15)	0.83	0.17	U	5780	477	100	100	83	17	1203.53	611.24
	1	Green (FT 20 FT 10)	0.17	0.83	S	378	5906	77	78	12	65	95.25	307.00
	2	Green (FT 20 FT 10)	0.33	0.67	S	1149	3381	115	115	38	77	294.00	446.71
	3	Green (FT 20 FT 10)	0.67	0.33	S	3645	1971	108	108	72	36	284.25	270.00
	4	Green (FT 20 FT 10)	0.83	0.17	S	4571	1619	120	120	100	20	451.75	156.00
	5	Green (FT 20 FT 10)	0.17	0.83	U	143	11889	112	113	19	93	229.55	961.40
	6	Green (FT 20 FT 10)	0.33	0.67	U	823	6606	110	114	35	74	383.82	746.85
	7	Green (FT 20 FT 10)	0.67	0.33	U	2394	2636	95	93	63	31	499.68	718.83
	8	Green (FT 20 FT 10)	0.83	0.17	U	3972	2177	114	113	95	19	626.88	909.77
162	1	Red (FT 10 FT 20)	0.17	0.83	S	4416	2151	119	116	20	96	321.14	459.88
	2	Red (FT 10 FT 20)	0.33	0.67	S	4690	1638	120	120	40	80	623.00	460.75

APPENDIX

(Continued)

Dependent Scheduling Group		<i>p</i> (Left)	<i>p</i> (Right)	Sig/ Unsig	<i>B<sub>L</sub></i>	<i>B<sub>R</sub></i>	<i>e<sub>L</sub></i>	<i>e<sub>R</sub></i>	<i>r<sub>L</sub></i>	<i>r<sub>R</sub></i>	<i>rt<sub>L</sub></i>	<i>rt<sub>R</sub></i>
Condition	Component											
	3 Red (FT 10 FT 20)	0.67	0.33	S	7649	380	120	117	80	40	1262.00	329.58
	4 Red (FT 10 FT 20)	0.83	0.17	S	12181	271	120	120	100	20	1153.50	109.00
	5 Red (FT 10 FT 20)	0.17	0.83	U	694	7189	112	109	19	90	957.32	1147.75
	6 Red (FT 10 FT 20)	0.33	0.67	U	5229	589	114	114	38	74	1201.83	987.71
	7 Red (FT 10 FT 20)	0.67	0.33	U	8008	216	120	120	80	40	1254.00	442.75
	8 Red (FT 10 FT 20)	0.83	0.17	U	11022	112	102	103	86	14	1477.67	511.88
	1 White (FT 15 FT 15)	0.17	0.83	S	1272	5682	120	120	20	99	214.00	591.79
	2 White (FT 15 FT 15)	0.33	0.67	S	1890	5028	119	120	40	80	453.55	663.33
	3 White (FT 15 FT 15)	0.67	0.33	S	6566	1006	120	120	80	40	920.00	458.67
	4 White (FT 15 FT 15)	0.83	0.17	S	7594	867	119	119	99	19	961.94	182.12
	5 White (FT 15 FT 15)	0.17	0.83	U	173	7318	97	92	16	76	613.43	1234.64
	6 White (FT 15 FT 15)	0.33	0.67	U	1698	5587	117	118	39	80	388.25	1319.27
	7 White (FT 15 FT 15)	0.67	0.33	U	3774	939	120	120	80	40	1239.00	413.67
	8 White (FT 15 FT 15)	0.83	0.17	U	13268	166	117	115	97	19	1361.50	848.80
	1 Green (FT 20 FT 10)	0.17	0.83	S	469	10089	120	119	20	99	87.50	975.91
	2 Green (FT 20 FT 10)	0.33	0.67	S	811	8364	120	120	40	80	125.50	930.00
	3 Green (FT 20 FT 10)	0.67	0.33	S	4124	1723	120	120	80	40	357.25	528.00
	4 Green (FT 20 FT 10)	0.83	0.17	S	4940	2111	118	118	98	19	624.00	264.60
	5 Green (FT 20 FT 10)	0.17	0.83	U	135	10831	106	109	18	91	396.16	1472.50
	6 Green (FT 20 FT 10)	0.33	0.67	U	192	9356	113	114	38	77	296.85	1467.59
	7 Green (FT 20 FT 10)	0.67	0.33	U	2231	2371	118	117	78	38	901.58	629.50
	8 Green (FT 20 FT 10)	0.83	0.17	U	7131	713	113	117	94	18	1049.32	1226.40
163	1 Red (FT 10 FT 20)	0.17	0.83	S	414	3683	69	65	10	53	163.40	497.38
	2 Red (FT 10 FT 20)	0.33	0.67	S	1325	4675	104	109	34	73	201.36	191.65
	3 Red (FT 10 FT 20)	0.67	0.33	S	7778	769	118	120	78	40	218.80	67.61
	4 Red (FT 10 FT 20)	0.83	0.17	S	6098	425	80	81	66	14	500.00	91.61
	5 Red (FT 10 FT 20)	0.17	0.83	U	292	6657	83	83	15	70	324.90	182.45



APPENDIX

(Continued)

Dependent Scheduling Group			$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$
Condition	Component												
	6	Red (FT 10 FT 20)	0.33	0.67	U	4493	840	90	89	31	60	371.83	198.48
	7	Red (FT 10 FT 20)	0.67	0.33	U	8985	88	69	71	47	22	266.50	80.95
	8	Red (FT 10 FT 20)	0.83	0.17	U	17281	120	99	103	83	18	300.00	228.95
	1	White (FT 15 FT 15)	0.17	0.83	S	501	5830	87	87	14	73	154.67	721.00
	2	White (FT 15 FT 15)	0.33	0.67	S	733	5539	107	110	35	74	119.96	298.87
	3	White (FT 15 FT 15)	0.67	0.33	S	6046	1116	110	115	72	40	120.17	116.73
	4	White (FT 15 FT 15)	0.83	0.17	S	7540	532	106	105	89	19	393.00	141.24
	5	White (FT 15 FT 15)	0.17	0.83	U	154	9679	77	78	15	64	338.67	244.33
	6	White (FT 15 FT 15)	0.33	0.67	U	2572	2402	93	90	30	59	224.60	238.33
	7	White (FT 15 FT 15)	0.67	0.33	U	8245	308	93	92	63	31	174.17	154.70
	8	White (FT 15 FT 15)	0.83	0.17	U	12285	157	99	98	83	16	282.60	397.17
	1	Green (FT 20 FT 10)	0.17	0.83	S	340	9123	96	96	16	80	138.00	873.50
	2	Green (FT 20 FT 10)	0.33	0.67	S	462	6322	101	105	33	70	89.44	448.48
	3	Green (FT 20 FT 10)	0.67	0.33	S	2224	3208	120	120	80	40	154.50	214.50
	4	Green (FT 20 FT 10)	0.83	0.17	S	6394	732	106	112	89	20	357.50	188.35
	5	Green (FT 20 FT 10)	0.17	0.83	U	195	14930	101	101	17	83	370.00	467.50
	6	Green (FT 20 FT 10)	0.33	0.67	U	163	7075	78	80	26	55	139.75	413.50
	7	Green (FT 20 FT 10)	0.67	0.33	U	1954	1966	57	57	38	19	91.08	151.83
	8	Green (FT 20 FT 10)	0.83	0.17	U	6645	356	79	79	66	13	178.38	675.00
164	1	Red (FT 10 FT 20)	0.17	0.83	S	813	5344	117	113	19	93	219.41	174.84
	2	Red (FT 10 FT 20)	0.33	0.67	S	5323	1240	111	112	36	75	290.50	153.75
	3	Red (FT 10 FT 20)	0.67	0.33	S	7452	383	120	119	80	40	200.00	78.70
	4	Red (FT 10 FT 20)	0.83	0.17	S	6407	324	120	120	100	20	153.50	131.00
	5	Red (FT 10 FT 20)	0.17	0.83	U	981	4299	102	101	19	84	646.86	597.34
	6	Red (FT 10 FT 20)	0.33	0.67	U	2702	2436	114	112	39	75	549.08	642.10
	7	Red (FT 10 FT 20)	0.67	0.33	U	8072	752	117	117	76	37	276.32	571.30
	8	Red (FT 10 FT 20)	0.83	0.17	U	8242	284	92	94	75	14	306.20	388.84

APPENDIX

(Continued)

Dependent Scheduling Group		<i>p</i> (Left)	<i>p</i> (Right)	Sig/ Unsig	<i>B<sub>L</sub></i>	<i>B<sub>R</sub></i>	<i>e<sub>L</sub></i>	<i>e<sub>R</sub></i>	<i>r<sub>L</sub></i>	<i>r<sub>R</sub></i>	<i>rt<sub>L</sub></i>	<i>rt<sub>R</sub></i>
Condition	Component											
1	White (FT 15 FT 15)	0.17	0.83	S	450	6432	117	118	19	98	107.39	243.56
2	White (FT 15 FT 15)	0.33	0.67	S	687	6086	117	116	38	77	133.17	212.52
3	White (FT 15 FT 15)	0.67	0.33	S	4425	2530	120	117	80	38	344.67	198.59
4	White (FT 15 FT 15)	0.83	0.17	S	5510	864	120	120	100	20	101.00	247.67
5	White (FT 15 FT 15)	0.17	0.83	U	456	7229	113	114	19	96	634.80	631.33
6	White (FT 15 FT 15)	0.33	0.67	U	568	6294	117	116	38	77	75.39	732.83
7	White (FT 15 FT 15)	0.67	0.33	U	4792	1507	117	119	76	40	178.83	470.79
8	White (FT 15 FT 15)	0.83	0.17	U	7573	637	114	115	94	19	346.77	799.51
1	Green (FT 20 FT 10)	0.17	0.83	S	249	9122	115	116	19	96	61.93	369.62
2	Green (FT 20 FT 10)	0.33	0.67	S	397	8883	115	114	36	77	59.73	411.00
3	Green (FT 20 FT 10)	0.67	0.33	S	1699	5265	118	115	78	38	117.95	418.79
4	Green (FT 20 FT 10)	0.83	0.17	S	4208	1159	105	101	87	15	93.52	511.14
5	Green (FT 20 FT 10)	0.17	0.83	U	159	10634	103	103	16	85	322.75	678.25
6	Green (FT 20 FT 10)	0.33	0.67	U	296	9458	117	116	38	76	40.00	632.82
7	Green (FT 20 FT 10)	0.67	0.33	U	1538	5402	118	119	79	40	92.95	838.00
8	Green (FT 20 FT 10)	0.83	0.17	U	6204	1140	116	115	96	18	453.21	941.93

Independent Scheduling Group		<i>p</i> (Left)	<i>p</i> (Right)	Sig/ Unsig	<i>B<sub>L</sub></i>	<i>B<sub>R</sub></i>	<i>e<sub>L</sub></i>	<i>e<sub>R</sub></i>	<i>r<sub>L</sub></i>	<i>r<sub>R</sub></i>	<i>rt<sub>L</sub></i>	<i>rt<sub>R</sub></i>
Condition	Component											
185	1 Red (FT 10 FT 20)	0.17	0.83	S	1681	2807	118	122	18	102	146.27	78.07
	2 Red (FT 10 FT 20)	0.33	0.67	S	1995	2296	122	118	40	77	133.88	123.32
	3 Red (FT 10 FT 20)	0.67	0.33	S	5099	1100	128	112	87	36	526.70	59.98
	4 Red (FT 10 FT 20)	0.83	0.17	S	7053	553	151	89	127	11	831.65	59.31
	5 Red (FT 10 FT 20)	0.17	0.83	U	1572	2927	112	118	20	102	196.10	97.96
	6 Red (FT 10 FT 20)	0.33	0.67	U	2284	3011	122	118	42	78	196.16	123.55
	7 Red (FT 10 FT 20)	0.67	0.33	U	10373	437	169	71	115	24	464.89	46.30
	8 Red (FT 10 FT 20)	0.83	0.17	U	12348	28	212	8	175	0	400.99	28.50
	1 White (FT 15 FT 15)	0.17	0.83	S	1813	2591	121	119	22	97	62.52	126.92
	2 White (FT 15 FT 15)	0.33	0.67	S	1614	2407	115	125	40	86	76.79	125.78
	3 White (FT 15 FT 15)	0.67	0.33	S	4183	1380	128	112	85	37	136.20	87.81

APPENDIX

(Continued)

Independent Scheduling Group													
Condition	Component	$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$	
4	White (FT 15 FT 15)	0.83	0.17	S	4036	1295	121	119	95	21	131.25	75.65	
5	White (FT 15 FT 15)	0.17	0.83	U	690	4220	91	149	14	122	78.37	124.70	
6	White (FT 15 FT 15)	0.33	0.67	U	1769	3370	117	122	35	78	89.55	155.25	
7	White (FT 15 FT 15)	0.67	0.33	U	3482	2294	123	117	77	38	138.25	130.49	
8	White (FT 15 FT 15)	0.83	0.17	U	11518	216	190	40	158	6	244.42	64.60	
1	Green (FT 20 FT 10)	0.17	0.83	S	991	3128	112	128	16	110	39.77	277.22	
2	Green (FT 20 FT 10)	0.33	0.67	S	1204	1764	104	116	35	74	64.36	236.55	
3	Green (FT 20 FT 10)	0.67	0.33	S	2275	1690	119	121	77	43	68.45	151.42	
4	Green (FT 20 FT 10)	0.83	0.17	S	2748	1656	122	118	105	22	102.85	134.42	
5	Green (FT 20 FT 10)	0.17	0.83	U	243	4708	44	129	10	107	71.25	220.44	
6	Green (FT 20 FT 10)	0.33	0.67	U	350	5967	52	187	22	130	58.60	356.66	
7	Green (FT 20 FT 10)	0.67	0.33	U	1499	3672	108	132	74	43	68.19	316.09	
8	Green (FT 20 FT 10)	0.83	0.17	U	3099	1284	121	107	101	21	104.36	163.91	
Condition	Component	$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$	
186	1 Red (FT 10 FT 20)	0.17	0.83	S	2288	5065	110	123	19	103	277.12	170.41	
	2 Red (FT 10 FT 20)	0.33	0.67	S	7701	1328	143	94	48	63	231.26	152.32	
	3 Red (FT 10 FT 20)	0.67	0.33	S	9574	497	164	74	109	21	236.68	124.54	
	4 Red (FT 10 FT 20)	0.83	0.17	S	15532	106	212	25	177	4	333.95	89.00	
	5 Red (FT 10 FT 20)	0.17	0.83	U	2963	3264	102	99	17	82	683.58	139.55	
	6 Red (FT 10 FT 20)	0.33	0.67	U	5485	1336	110	97	38	62	614.80	192.39	
	7 Red (FT 10 FT 20)	0.67	0.33	U	8252	510	141	98	93	30	632.81	57.19	
	8 Red (FT 10 FT 20)	0.83	0.17	U	13938	25	220	16	181	0	431.20	50.50	
	1 White (FT 15 FT 15)	0.17	0.83	S	1179	5505	84	148	22	125	186.03	169.00	
	2 White (FT 15 FT 15)	0.33	0.67	S	1333	5819	77	158	22	108	170.41	148.55	
	3 White (FT 15 FT 15)	0.67	0.33	S	5010	2928	122	118	80	42	209.76	146.66	
	4 White (FT 15 FT 15)	0.83	0.17	S	7926	1177	128	105	106	17	222.44	142.56	
	5 White (FT 15 FT 15)	0.17	0.83	U	74	7956	23	210	4	174	120.33	113.73	
	6 White (FT 15 FT 15)	0.33	0.67	U	181	5978	42	166	11	111	218.24	181.33	

APPENDIX

(Continued)

Independent Scheduling Group													
Condition	Component	$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$	
7	White (FT 15 FT 15)	0.67	0.33	U	5222	2622	117	106	76	37	447.33	247.84	
8	White (FT 15 FT 15)	0.83	0.17	U	10781	342	163	62	136	14	321.89	124.38	
1	Green (FT 20 FT 10)	0.17	0.83	S	357	7417	61	171	3	141	61.48	238.23	
2	Green (FT 20 FT 10)	0.33	0.67	S	432	7590	44	196	13	128	96.05	193.53	
3	Green (FT 20 FT 10)	0.67	0.33	S	1154	5271	81	155	55	51	173.20	121.16	
4	Green (FT 20 FT 10)	0.83	0.17	S	4504	3542	116	123	98	20	141.81	221.09	
5	Green (FT 20 FT 10)	0.17	0.83	U	27116	27	2	231	1	190	15.00	215.34	
6	Green (FT 20 FT 10)	0.33	0.67	U	18	8065	8	187	3	127	59.00	399.51	
7	Green (FT 20 FT 10)	0.67	0.33	U	4067	4001	112	114	76	40	271.70	603.22	
8	Green (FT 20 FT 10)	0.83	0.17	U	4247	2542	108	115	92	20	246.29	278.36	
Condition	Component	$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$	
187	1 Red (FT 10 FT 20)	0.17	0.83	S	953	2208	99	120	20	99	345.68	599.60	
	2 Red (FT 10 FT 20)	0.33	0.67	S	1908	1634	102	100	37	67	556.61	216.30	
	3 Red (FT 10 FT 20)	0.67	0.33	S	4056	284	134	77	85	22	613.22	74.59	
	4 Red (FT 10 FT 20)	0.83	0.17	S	3389	55	119	25	97	6	529.78	98.45	
	5 Red (FT 10 FT 20)	0.17	0.83	U	1106	2026	110	122	17	99	424.32	273.78	
	6 Red (FT 10 FT 20)	0.33	0.67	U	2876	755	132	105	43	71	330.45	54.70	
	7 Red (FT 10 FT 20)	0.67	0.33	U	4984	311	144	92	102	24	264.99	34.54	
	8 Red (FT 10 FT 20)	0.83	0.17	U	7173	78	184	31	160	0	924.16	45.00	
	1 White (FT 15 FT 15)	0.17	0.83	S	1359	2647	98	110	12	95	188.09	897.01	
	2 White (FT 15 FT 15)	0.33	0.67	S	1349	2540	102	115	28	80	330.66	736.88	
	3 White (FT 15 FT 15)	0.67	0.33	S	3826	882	130	99	89	34	461.17	308.09	
	4 White (FT 15 FT 15)	0.83	0.17	S	2105	15	93	9	80	1	335.50	29.20	
	5 White (FT 15 FT 15)	0.17	0.83	U	294	3665	84	141	19	123	158.47	863.18	
	6 White (FT 15 FT 15)	0.33	0.67	U	1077	1271	105	101	35	61	143.28	194.21	
	7 White (FT 15 FT 15)	0.67	0.33	U	2305	637	98	82	66	26	107.65	81.48	
	8 White (FT 15 FT 15)	0.83	0.17	U	4828	205	151	58	122	11	256.28	71.50	
	1 Green (FT 20 FT 10)	0.17	0.83	S	704	2527	84	100	17	82	196.31	894.16	
	2 Green (FT 20 FT 10)	0.33	0.67	S	384	2668	84	109	28	71	135.97	896.99	

APPENDIX

(Continued)

Independent Scheduling Group													
Condition	Component	$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$	
3	Green (FT 20 FT 10)	0.67	0.33	S	1254	2415	98	103	65	33	215.62	375.84	
4	Green (FT 20 FT 10)	0.83	0.17	S	2598	8	194	5	160	0	342.28	18.00	
5	Green (FT 20 FT 10)	0.17	0.83	U	50	5613	34	181	6	148	62.75	1079.35	
6	Green (FT 20 FT 10)	0.33	0.67	U	694	2202	112	128	38	87	72.68	425.34	
7	Green (FT 20 FT 10)	0.67	0.33	U	1316	1250	107	109	67	42	82.34	317.55	
8	Green (FT 20 FT 10)	0.83	0.17	U	3916	166	161	60	130	12	134.23	143.12	
Condition	Component	$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$	
188	1	Red (FT 10 FT 20)	0.17	0.83	S	3304	1420	105	96	15	78	280.63	132.54
	2	Red (FT 10 FT 20)	0.33	0.67	S	3933	1334	124	116	41	76	322.54	163.42
	3	Red (FT 10 FT 20)	0.67	0.33	S	8208	134.5	180	43	122	10	431.73	53.03
	4	Red (FT 10 FT 20)	0.83	0.17	S	8820	8	191	4	158	0	731.03	10.50
	5	Red (FT 10 FT 20)	0.17	0.83	U	1289	1588	88	99	14	81	438.63	283.56
	6	Red (FT 10 FT 20)	0.33	0.67	U	1981	1017	95	85	36	56	495.40	179.56
	7	Red (FT 10 FT 20)	0.67	0.33	U	5495	120	145	57	97	18	886.45	74.27
	8	Red (FT 10 FT 20)	0.83	0.17	U	5042	98	144	46	125	6	710.99	49.98
	1	White (FT 15 FT 15)	0.17	0.83	S	1779	2968	106	117	22	101	188.83	293.47
	2	White (FT 15 FT 15)	0.33	0.67	S	1729	2668	103	111	36	75	167.32	296.54
	3	White (FT 15 FT 15)	0.67	0.33	S	3702	1507	114	110	73	37	252.31	157.69
	4	White (FT 15 FT 15)	0.83	0.17	S	7580	215	145	71	124	13	319.24	107.13
	5	White (FT 15 FT 15)	0.17	0.83	U	277	3889	66	150	10	125	124.84	531.54
	6	White (FT 15 FT 15)	0.33	0.67	U	1195	2018	91	103	33	68	170.58	328.31
	7	White (FT 15 FT 15)	0.67	0.33	U	2592	1081	115	115	75	37	513.86	277.13
	8	White (FT 15 FT 15)	0.83	0.17	U	4239	223	146	80	120	11	567.63	119.24
	1	Green (FT 20 FT 10)	0.17	0.83	S	597	4565	87	136	13	111	83.44	464.86
	2	Green (FT 20 FT 10)	0.33	0.67	S	1570	3223	111	125	38	81	108.15	534.49
	3	Green (FT 20 FT 10)	0.67	0.33	S	2219	1972	98	96	66	34	172.26	277.56
	4	Green (FT 20 FT 10)	0.83	0.17	S	5949	288	134	77	108	9	225.94	158.67
	5	Green (FT 20 FT 10)	0.17	0.83	U	33	4344	20	141	4	118	31.20	746.10

APPENDIX  
(Continued)

Independent Scheduling Group													
Condition	Component	$p(\text{Left})$	$p(\text{Right})$	Sig/ Unsig	$B_L$	$B_R$	$e_L$	$e_R$	$r_L$	$r_R$	$rt_L$	$rt_R$	
6	Green (FT 20 FT 10)	0.33	0.67	U	63	3770	28	126	5	84	85.30	432.36	
7	Green (FT 20 FT 10)	0.67	0.33	U	1054	1530	98	101	63	35	356.81	604.96	
8	Green (FT 20 FT 10)	0.83	0.17	U	2583	303	131	81	108	18	334.70	332.79	